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Smart and Just Grids for sub-Saharan Africa: Exploring options

Manuel Welsch [a,*], Morgan Bazilian [a,b], Mark Howells [a], Deepak Divan [c], David Elzinga [d], Goran Strbac [e], Lawrence Jones [f], Andrew Keane [g], Dolf Gielen [h], V.S.K. Murthy Balijepalli [i], Abeeku Brew-Hammond [j], Kandeh Yumkella [k]

[a] KTH Royal Institute of Technology, Stockholm, Sweden
[b] International Institute for Applied Systems Analysis, Laxenburg, Austria
[c] Georgia Institute of Technology, Atlanta, GA 30332-0250, USA
[d] International Energy Agency, Paris, France
[e] Imperial College London, London, UK
[f] ALSTOM Grid, Washington DC, USA
[g] University College Dublin, Dublin, Ireland
[h] International Renewable Energy Agency, Bonn, Germany
[i] Indian Institute of Technology, Bombay, India
[j] Kwame Nkrumah University of Science and Technology, Kumasi, Ghana
[k] United Nations Industrial Development Organization, Vienna, Austria

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ABSTRACT

In 2009, an estimated 585 million people had no access to electricity services in sub-Saharan Africa. Unlike many other regions of the world, under current assumptions, that figure is expected to rise significantly to about 652 million by 2030-an unsustainable and unacceptable situation. Knowing of the intrinsic linkages between access to energy services and development, national governments and regional organisations have identified the urgent need for accelerated electrification rates. Some of the established and emerging concepts, systems and technologies grouped under the term 'Smart Grids' may offer an important contribution to achieving universal access to electricity.

We argue that these Smart Grid advances may enable sub-Saharan African countries to leapfrog elements of traditional power systems and accelerate and improve electrification efforts. We introduce the notion of Just Grids to reflect the need for power systems to contribute towards equitable and inclusive economic and social development without marginalising the poor. The paper reviews the literature, and identifies specific options that could be implemented in sub-Saharan Africa. After selecting criteria that focus on potential impact as well as requirements for their implementation, a qualitative first-pass assessment of the potential of these options is made. This paper provides support for policy development, and suggests areas for further, more detailed research.

Contents

* Corresponding author. Tel.: +46 87907682.
E-mail address: manuel.welsch@energy.kth.se (M. Welsch).

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1. Introduction

According to the reference scenario in the World Energy Outlook [1], Africa's final electricity consumption is expected to double between 2007 and 2030 from 505 to 1012 TWh. Over the same time period, the United Nations (UN) Secretary-General's Advisory Group on Energy and Climate Change (AGECC) has proposed that the UN System and Member States commit to ensuring universal access to reliable, affordable and sustainable modern energy services by 2030 [2].

We propose that specific elements of current and emerging Smart Grid[1] concepts, systems and technologies might make an important contribution to achieving this goal by accelerating equitable and just access to electricity services in sub-Saharan Africa [3]. While this might include elements that are currently in the centre of attention in industrialised countries, some options might also emerge which explicitly address developing country needs.

In Section 2, a selective description of the electricity sector in sub-Saharan Africa is provided. Section 3 continues with a concise review of current Smart Grid concepts, projects and expected benefits. Section 4 places the Smart Grids concept in the context of sub-Saharan African, shifting the focus towards the facilitation of just access. It then illustrates potential opportunities for leapfrogging elements of traditional power systems.[2] Section 5 identifies selected Smart and Just Grid options with a potential role in the near- to medium-term. Section 6 introduces and provides background on criteria by which these options might be assessed. The selected criteria include: consumers; operation & quality of supply; generation; environment; technical complexity; finance; human capacities; policy, regulation & standards; and modelling. Based on these criteria, Section 7 provides an indicative assessment of the potential of these options. Section 8 suggests next steps to inform international cooperation, complementary to regional and national initiatives in sub-Saharan Africa. Finally, the paper concludes with Section 9. This study represents only an initial set of thoughts to support policy considerations and further research.

2. Electricity in sub-Saharan Africa

In 2009, around 585 million people in sub-Saharan Africa (about 70% of the population) had no access to electricity services [4]. This figure is expected to rise significantly to about 652 million people by 2030. 85% of those without access to electricity live in rural areas [5]. In addition to low energy access rates, the energy sector is characterised by several other significant challenges including: electricity costs as high as USD 0.50/kWh, insufficient generation capacity to meet rapidly rising demand, and poor reliability of supply [6]. The estimated economic value of power outages in Africa amounts to as much as 2% of GDP, and 6–16% in lost turnover for enterprises [7].

In 2008, sub-Saharan Africa generated 380 TWh of electricity, of which South Africa alone produced almost 70% [8].[3] For a sense of scale, with 68 GW, the entire generation capacity of sub-Saharan Africa is no more than that of Spain.[4] In addition, sub-Saharan Africa's average generation capacity was only about 100 MW per million inhabitants in 2009, ranging from less than 15 MW per million inhabitants in Guinea-Bissau and Togo, to 900 in South Africa, and up to 1080 in the Seychelles [11]. By comparison, the generation capacity is about 1680 MW per million inhabitants in the European Union, and 3340 MW per million inhabitants in the U.S.

The significant need for accelerated electrification rates has been identified by regional (economic) communities[5] and is largely underpinned by national electrification policies. More than 75% of sub-Saharan countries having defined targets for electricity access [12]. The importance of regional and national electrification initiatives is clearly understood at the policy level. The priority is to translate this understanding into provision of electricity services 'on the ground'.

3. A Smart Grid approach

The term 'Smart Grid' has come to encompass a range of innovative tools, technologies and practices envisioned to be supported by novel business models and regulatory frameworks. All of them ultimately should serve to help ensure a reliable, secure and economically efficient supply of electricity services. While there is consensus on this overall objective, the precise scope of the term Smart Grids is interpreted differently according

[1] It remains the case that modern power system planning and operational tools and systems currently employed in the OECD also have much to offer developing countries.

[2] We use the term *electricity infrastructure* or *power systems* to encompass the entirety of the system, from generation through transmission and distribution to customer services and associated operations.

[3] Refer to Niez [9] for more details on South Africa's electricity sector and policies.

[4] Without South Africa, this capacity goes down to 28 GW, 25% of which is currently not available for generation due to, amongst others, aging plants and lack of maintenance [10].

[5] Such as: The Forum of Energy Ministers of Africa's (FEMA) Position Paper on Energy and the MDGs [12]; The Southern African Development Community's (SADC) Protocol on Energy [13] and its Regional Indicative Strategic Development Plan (RISDP) [14]; The Economic Community Of West African States' (ECOWAS) Energy Protocol [15] and its White Paper for a Regional Policy [16]; The Common Market for Eastern and Southern Africa's (COMESA) Energy Programme [17]; The East African Community's (EAC) Regional Strategy on Scaling-up Access to Modern Energy Services [18] and its Power Master Plan Study [19]; The Treaty Establishing the Economic Community of Central African States [20]; The Economic and Monetary Community of Central Africa's (CEMAC) Energy Action plan with energy and electricity access goals [12]; the Africa-EU Energy Partnership [21,22].

to perspective and environment,[6] and it continues to evolve (see, e.g., [24–29]. Much of the literature focuses on how Smart Grids could help establish a two-way flow of information between supplier and user to increase the efficiency of network operations [30–36], yet a common functional and technical definition has not emerged [27].

For our purposes, Smart Grids is a broad concept that covers the entire electricity supply chain and is characterised by the use of technologies to intelligently integrate the generation, transmission and consumption of electricity [37]. Thus, Smart Grids elements are part of a continuum of power sector tools and technologies.

Smart Grids are expected to allow to some level dynamic balancing and optimisation of generation, delivery assets and loads. Associated key technical benefits may include: improved reliability and resilience, cost-effective integration of variable resources and loads, increased efficiency of system operation, and optimised utilisation of both generation and grid infrastructure assets.[7] For example, through the facilitation of demand response measures Smart Grids may allow shifting loads from peak to off-peak periods. This may help increase the utilisation of existing power plants and defer future investments in grid and generation capacities. Smart Grids may deliver these benefits at potentially lower overall cost than would be possible under business-as-usual assumptions. Detailed assessments of the cost implications for utilities, consumers and society will be required to justify specific investments [29].

Many countries are engaged in programmes and pilot projects to test Smart Grid concepts,[8] for example: the Jeju Island project in South Korea [40–43]; China's Strong and Smart Grid Roadmap [44], initiatives in Yangzhou, China [45]; Yokohama, Japan [46]; and Boulder, Colorado, U.S. [34]; the TWENTIES [47] and EcoGrid EU projects in the European Union [48,49]; and planned smart grid applications for Masdar City, United Arab Emirates [50].[9] While not much precedence seems to exist in Africa, South Africa launched the South African Smart Grid Initiative (SASGI) [53,54] and the Smart Grid technology company BPL Global has signed a 5-year modern grid contract with Ghana's national utility [55].

Building on existing and anticipated experiences from such initiatives will help assess sub-Saharan Africa's potential to profit from Smart Grids. It will provide valuable input on how to refine existing concepts and associated policies to optimise their cost-benefit balance in a sustainable manner.

4. Smart and Just Grids in the sub-Saharan African context

Employing a subset of envisioned Smart Grid advances may enable sub-Saharan African countries to leapfrog traditional power systems and ramp-up efforts to reach more effective solutions. This could accelerate national and regional electrification timeframes, while improving service and minimising costs and environmental impact. We introduce the term Just Grids to reflect the importance for power systems to contribute towards equitable and inclusive global economic and social development. Given the specific needs of sub-Saharan Africa, it is suggested that a Smart Grid approach for this region cannot simply be a copy of practices in industrialised countries—the starting point, challenges and opportunities are often too different.

4.1. A new emphasis

We broadly define the concept of Smart and Just Grids for sub-Saharan Africa as one that embraces all measures in support of short-term and future integration of advanced two-way communication, automation and control technologies into local, national and regional electricity infrastructure. Accelerated access to electricity services may be facilitated through optimising grid systems, operations and technologies. This would allow for a potentially higher penetration of variable renewable energy sources and improvements to the reliability and economic efficiency of electricity supply.[10] In addition to being smart, socially just[11] power systems are required in sub-Saharan Africa in order to promote access to modern energy services without marginalising the poor.[12]

In the future, Smart *and* Just Grids in sub-Saharan Africa could provide similar functionality to Smart Grids in industrialised countries at full deployment, even though they may follow a different development pathway and timeframe. The diversity of the electrification status in sub-Saharan Africa,[13,14] means that lessons learned from other regions may be directly applied in certain areas, while tailored solutions will be required for others. Constraints such as a lack of limited investment capital, largely inadequate institutional and physical infrastructure, and a gap in well-trained power sector personnel are likely stifling innovative practices that could already be occurring organically.[15]

In order to realise the potential of Smart and Just Grids in sub-Saharan Africa, creating an enabling environment is therefore essential. Below we summarise some key aspects of such an environment that should be addressed by policy makers, investors and other stakeholders, with specific reference to the sub-Saharan African context.

Smart policies: Defining common ground rules for integrating technologies and business practices, identifying better ways to support effective demand-side management, and developing new policies to support the integration of distributed generation. All

[6] For example, according to J. Antonoff, the U.S. focuses on technologies while the EU prioritises policies and strategies, assuming that technologies will follow [23].

[7] Based largely on improved communication and increased interoperability at all grid levels [38].

[8] India actively supports Smart Grid developments through the restructured accelerated power development and reforms programme (R-APDRP) [39].

[9] For further information on pilot projects and policies refer to Doran et al. [36]. For a U.S. focus and information on dynamic pricing and pilot design principles refer to Faruqui et al. [51]. The consumer response to smart appliances combined with pricing signals was assessed in a project described in Chassin D. P. [52].

[10] Note that increases in variable renewable energy generation might require parallel investments in supportive infrastructure to maintain reliability requirements. Such investments could target storage options, the distribution and/or transmission grid, and generation and demand response options for the provision of reserve services [56]. Refer to Söder and Amelin [57,58] for methods to quantify the contribution of wind power to the reliability of the power system. Milligan et al. [59] and Hand et al. [60] provide assessments of the implications of high levels of renewable electricity generation, focusing on grid integration aspects in the U.S.

[11] According to Zajda, Majhanovich, and Rust [61], social justice generally refers to, "an egalitarian society that is based on the principles of equality and solidarity, that understands and values human rights, and that recognizes the dignity of every human being".

[12] Similarly, UNEP [62] calls for a just transition to a sustainable, low-carbon economy to ensure that social aspects are equitably integrated into economic and environmental considerations, and that emerging opportunities are adequately shared among stakeholders.

[13] Wide variations in the energy sector can be demonstrated by per capita energy consumption, which varies from some 20 kgoe in Burundi to 860 kgoe in Zimbabwe, correlating well with respective GNP per capita [63].

[14] This diversity is comparable to India, which may offer a significant potential to learn from its Smart Grid developments. Refer to Balijepalli et al. [39] and Balijepalli et al. [64] for a focus on India's related endeavours.

[15] For example, the electrification of New York started with Thomas Edison's effort to develop a successful business, covering the complete system of electric generation, distribution and appliances (the light bulb) [65,66].

such policies would need to be underpinned by well-defined performance goals and transparent metrics to ensure effective monitoring of anticipated benefits.

Focus for sub-Saharan Africa: Leveraging international Smart Grid frameworks, legislation, regulation and standards, and adjusting them to the sub-Saharan African context[16] will be essential. New policies may need to diverge from international precedent, in order to respond to rapid demand growth and urbanisation, reduce theft of electricity and utility assets, and prioritise access to affordable electricity services[17] for the poor, supported by simplified requirements for rural electrification schemes. Such policies should enable access through flexible, no-regret electrification strategies that accommodate expansions of stand-alone systems, mini and national grids, and that support their integration.[18]

Smart planning: Adjusting the grid to local circumstances and developing design principles that ensure an effective interoperability of existing and new grids, leading to even smarter networks over time.

Focus for sub-Saharan Africa: A balanced approach between regional grid integration,[19] national grid enhancements and decentralised mini-grids is required. While smart mini-grids, such as those described in [69], may provide a short-term solution to rural electrification needs, their future integration into national and regional grids and vice-versa should be an integral consideration of power system planning.

Smart systems: Guaranteeing the security and quality of supply through smart automation and control arrangements, building on load management and integration of distributed energy sources, for mini, national and regional grids, as shown in [70].[20]

Focus for sub-Saharan Africa: Country and locally appropriate supply quality standards will need to be derived. These may initially be less stringent than current practices in industrialised countries and may vary by class of service. Increasing the grid's load factor through demand side management may also significantly help reduce costs, especially for rural electrification schemes [71]. Ultimately, a strong high voltage (HV) grid may be developed as a backbone of the power system, especially to foster electricity intensive industrial growth.

Smart technologies: Deploying proven smart technologies, optimising interoperability with emerging technologies, and developing future solutions to best address electrification needs [72,73].

Focus for sub-Saharan Africa: The technology deployment path will vary widely at regional and country levels due to diverse needs and goals of different societies and markets. Defining these technology pathways and markets and verifying them through pilot projects will be important first steps.

Smart people: Building stakeholder capacity[21] to facilitate the transition to Smart Grids, to operate the grids, and to attract and actively engage the private sector and consumers so that as many people as possible profit from the transition.

Focus for sub-Saharan Africa: Educating consumers in sub-Saharan Africa about efficient electricity use whilst moving towards Smart Grids will be essential, especially for those who previously had no access. Training tools and materials about state-of-the-art power systems will also need to be widely disseminated to analysts and technicians. Specific attention needs to be paid to the training of off-grid communities so they can manage and maintain mini-grid systems in a sustainable fashion.

Responsibility for ensuring that grids as a public good are smart *and* just falls mainly on governments and utilities. The following Just Grid characteristics are especially relevant to sub-Saharan Africa:

Just access: Ensuring universal access to electricity by:

- Encouraging electricity to be tapped-off from larger grid extension projects to local customers en-route. Connections for large consumers are often the primary driver for grid extensions. Such extensions may offer a great opportunity to connect the under-served at the same time[22];
- Using grid technologies that can cope with fluctuating supply and demand in rural areas and thus increase quality of supply, for example by building on strategic load control and management instead of conventional load shedding;
- Focusing on accelerated access to key electricity services rather than access to electricity in general. Doing this in a 'smart' way may help governments deliver on their development agendas more effectively and at lower cost, for example by prioritising electrical services required to specifically meet the Millennium Development Goals (MDGs) [75];
- Expanding service delivery under resource constraints by increasing the efficiency of electricity supply and use;
- Creating additional revenues for utilities through higher payment discipline enabled by advanced metering infrastructure, which might encourage utilities to extend services to new customers.

Smart and Just financing: Developing a commercially successful business model encompassing pricing, cost structure and sales. Creating flexible tariff structures and payment schemes to ensure affordable and sustainable access to electricity services, by:

- Realising the potential of Smart Grids to help lower prices of electricity services by optimising the utilisation of grid assets, segmenting electricity markets according to reliability and quality requirements, minimising technical and non-technical losses by promoting smart and efficient appliances, and increasing cost-effective integration of renewable energy in remote areas[23];

[16] Refer to Schwartz [67] for further information on policy support required to deliver Smart Grid benefits.

[17] This may even include a differentiation between individual services, ranked based on local priorities. For example hot water heating may be more 'interruptible' than say vaccine cooling in a clinic.

[18] For example, in remote areas photovoltaic (PV) panels can provide a limited and, thus at times, limiting quantum of electricity for customers. At present, such customers are considered 'electrified'. In the case of mini- or national grid extensions with better power quality, such customers may either not be targeted or the photovoltaic system left unused, as current systems are often not designed to integrate such home circuits or local grids. A Smart Grid may help provide limited initial access followed by improved bulk service supplies as stand-alone systems are integrated locally and nationally.

[19] As an example for regional grid integration, the Tres Amigas SuperStation in New Mexico, USA, will serve to improve grid reliability and solve voltage and stability issues by linking the three primary U.S. electricity transmission grids through high-voltage direct current converter technology [68].

[20] This represents a shift from traditional preventive control philosophy to corrective, 'just in time', control approach. Benefits include enhanced utilization of grid assets and improved efficiency. Supportive new techniques and tools for system operation and design need to be developed and applied. For example, at industrial and institutional levels, under-frequency protective relays for heating, cooling and motor loads can provide significant support for grid operation.

[21] This includes policy makers, government agencies, regulators, electricity network and service companies, traders, generators, finance institutions, technology providers, researchers and users.

[22] Note that past electrification efforts in now highly developed countries followed a similar pattern [74].

[23] This is especially true when diesel power generators are used: renewable energy provides a cost-competitive alternative, as fuel transport costs to provide diesel to remote locations in Africa are significantly higher than in most industrialised countries [76]. Costs for diesel power generation can range from USD 0.35 per kWh in Africa to more than USD 1 per kWh for Pacific islands and remote continental locations [77]. The use of locally available renewable resources

- Providing additional support programmes to identify and foster productive uses of electricity to help ensure that low-income consumers can pay for their required electricity services;
- Allowing for targeted subsidies through integrated smart billing to support 'basic' services such as food refrigeration, as opposed to 'luxury' services, like television. Ensure subsidy schemes are targeted towards the poor and provide incentives for utilities to expand access [78].

There is clearly a vast array of Smart Grid elements available to support this redefined concept. They are not all immediately relevant, however, and some are either not developed enough or at present prohibitively expensive to be usefully deployed in the sub-Saharan African context in the short- to medium-term. Avoiding technology lock-in will be crucial, as the economic lifetime of electric power equipment can be up to 50 years and longer [79,80].

4.2. Opportunities for leapfrogging

The opportunity for Smart and Just Grids to leapfrog[24] traditional power systems may mean that they can offer even more exciting opportunities to developing countries than to industrialised ones. While some components of Smart Grids offer a good basis for leapfrogging in the short-term, for others it will be essential to set the preconditions today required for enabling a transition to smarter networks as the technologies mature in the future.[25]

In the short term, we envision leapfrogging to occur mainly for the components based on information and communication technologies (ICT), which form an integral part of many Smart Grid systems. In certain cases, Africa already notably 'leapfrogged' to more efficient ICT solutions. Although not a perfect analogy, the information revolution[26] of the mid-1990s in sub-Saharan Africa linked to the use of mobile phones offers some useful lessons.

Africa became the world's fastest growing cell phone market [85] with growth rates in the order of 300% per annum in countries like Kenya and Cameroon [86]. Within 10 years, the number of mobile phone subscriptions in sub-Saharan Africa shot up from four per 100 people to 53 in 2011 [87]. The actual number of users is expected to be much higher still, due to people sharing their mobile phones, especially in poor communities[27] [89,90].

One reason for the mobile sector's great success was the failure of conventional telecommunication systems to meet consumer demand, both in terms of number of connections and quality [84]. This constitutes a parallel to the failure of current electricity networks in sub-Saharan Africa to meet the needs of millions of Africans. Another reason for the rapid diffusion of mobile phones was the lack of red-tape involved in registering for the pre-paid services that are used by 90% of mobile subscribers in sub-Saharan Africa [89].[28] Pre-paid subscriptions address especially the needs of people with lower or irregular incomes, as no bank account, mail address, or fixed monthly fee are required [91]. Smart and Just Grids could take advantage of ICT infrastructure to implement similar payment schemes.

In addition to technological reasons for leapfrogging, market models that accompanied the mobile phone revolution such as sharing phones may serve as a precedent for Smart Grids. Other success factors, which may not translate as seamlessly to Smart Grids, were the relatively low initial investments and the quick installation of re-deployable assets, making related initiatives less dependent on institutional frameworks and investor protection [92].

Mobile phones offered as well large benefits at low costs to consumers which were already connected to conventional telephone networks, both in terms of flexible payment schemes and increased availability. Overall, there was a strong drive by consumers to make the mobile phone revolution happen and telecom companies found themselves in a profitable space.

This constitutes a major flaw in this analogy. In the transition towards Smart Grids, mainly utilities and governments are expected to be the driving force. Effective market places still need to be developed. Further, apart from increased reliability in supply for existing consumers, especially those might benefit who gain accelerated access to electricity. This could be due to their connection to smart mini-grids or due to grid expansions facilitated by more efficient power systems.

5. Identifying specific options

In line with findings from the ETP SmartGrids [30], the implementation of Smart Grids for sub-Saharan Africa will, inter alia, require: a toolbox of proven technical solutions, harmonised regulatory and commercial frameworks, shared technical standards and protocols, and supportive ICT systems. It will be especially important to future-proof current grid infrastructure projects in a cost-effective way to ensure their compatibility with future plans to upgrade them to Smart Grids.

Particular elements of Smart and Just Grids could help offer tangible and direct benefits in the short- to medium-term, some of which are mentioned below. They comprise both elements which are currently focused on in industrialised countries as well as elements which might be of particular interest for developing countries. Options which are qualitatively assessed in the next section are shown in *italic and underlined.*

Transmission and substation design: Especially for longer transmission lines, the scale of technical losses can become considerable.[29] Smart Grids could help reduce such losses, for example by *improved power lines and transformers*, as well as facilitating maintenance schemes [9]. Existing substation transformers can be a significant source of total grid losses, being responsible for up to 40% [93]. For example, superconducting fault current limiting transformers can help improve system performance and efficiency [94]. Deploying low-sag, high-temperature conductors and dynamic line rating can significantly increase the electric current carrying capacity.

(*footnote continued*)
increases supply security both in physical terms and in terms of pricing. This is especially important for supporting growth of electricity-dependent small and medium enterprises and industrial customers.

[24] A definition of technology leapfrogging can be found in Davison et al. [81]. Examples of leapfrogging in developing countries in the field of energy are mentioned in Goldemberg [82].

[25] For example, latest conductor technology and controls could be used for current greenfield developments to ensure long-term flexibility for integrating energy sources [83].

[26] Wilson III and Wong [84] defined the information revolution as an institutional and policy revolution, highlighting the importance of private sector participation, foreign investment, competition and de-centralisation.

[27] Grameenphone has 6 million subscriptions in Bangladesh, 3% of which are for 'village phones', which are shared by a large number of users, and account for one-third of the traffic [88].

[28] Access rates are much higher than subscription rates, reaching almost 100% for some countries. This potential access is not directly beneficial for the large majority of the African people, who still cannot afford to pay for the services [89].

[29] For a sense of scale, Sebitosi and Okou [86] note that "the estimated amount of power that is lost during the delivery of 2000 MW from Cahora Bassa through the 1500 km line to South Africa is nearly equal to the entire consumption capacity of Mozambique, the host generating country".

Wide-area monitoring and control[30] could support the accurate information required for real-time decision making to respond better to disturbances within the system [93]. This will enhance utilisation of primary grid infrastructure and contribute to a more efficient system operation. Some of the required advanced transmission technologies[31] may target the more developed existing grids in sub-Saharan Africa, and may be disproportionate in areas with limited grid coverage. This is especially true since advanced monitoring and control requires integration throughout the transmission system, facilitated by sophisticated grid design techniques.

Distribution system design: While its benefits might be considerable, smartening the distribution system is significantly more challenging than improving the transmission networks [29]. *Distribution automation* technologies could help improve power systems by extending intelligent control [93]. For example, smart sensors and flexible and intelligent switches and interrupters at critical points on distribution circuits could minimise the extent of outages and increase the speed of restoration [96], while keeping cost increases at a minimum. Smart distribution technologies allowing for increased levels of distributed generation will be especially important for addressing rural electrification needs and minimise connection costs. The planning and design of these networks will require full horizon planning, i.e., a 20 year plus period. The development of these grids will be atypical, but existing work on distribution planning may provide a useful starting point [97].

Power theft often contributes significantly to overall system losses in developing countries,[32] reducing the economic performance of utilities. High-voltage distribution lines can help prevent illegal connections and improve power quality and reliability [9]. Smart metering infrastructure can help reduce theft further, e.g., through remote meter reading [99] combined with an independent transformer-loading based validation process.

Smart mini- and micro-grids: Mini-, and especially micro-, grids with high shares of renewable energy are generally complex to implement, primarily because of fluctuating generation and a low load factor.[33] The task of maintaining adequate power quality becomes a challenge, for example due to spikes associated with the starting current of motor loads [101] or the need to provide some form of back-up power. Smart components could help cushion such effects and better balance the overall system, e.g., through integrating new demand side management options. Costs of such systems may be further cut through the implementation of *(DC) micro-grids*, especially when combined with photovoltaic generation. While losses can be reduced through saving layers of DC/AC and AC/DC power conversion, the more expensive protective devices required for fault management and control, such as coordinated power converters, add complexity and outweigh some of the potential savings. Further, a potential future integration into AC grids requires consideration.

The smart integration of grids, from the micro- into the mini-grid and ultimately the national grid, will allow bringing together decentralised electrification with national electrification plans. As a result, there might be scope to reconsider future (grid-based) plant mixes. For example, cheap base load could be provided by the national grid, while the integrated decentralised grids could rather be geared towards contributing to the more expensive peak load, ultimately reducing the overall electricity price. At the mini-grid level, this may include the *integration of existing distributed generators*, e.g., a diesel generator from a hospital, which is especially worth considering when expanding the grid to previously un-electrified areas. Such generators are characterised by being close and well-adjusted to their consumer loads, which are supposedly often much higher than average household demand in sub-Saharan Africa. When applied for offsetting peak demand, they may allow owners to profit from cost reductions if combined with according pricing schemes. Utilities and society will profit from the capacity increases, especially during peak demand; improved quality of supply through increased flexibility; increased system efficiency with improved load factors; potentially lower emissions due to the reduced need for spinning reserves; and enhanced network security and resilience to price spikes, supply shortages and outages [102]. The economics of such integration has shown potential. Portland General Electric (PGE) estimates that integrating the installed distributed generation base in Portland, Oregon, USA, to offset peak power purchases could reduce the price per kWh by around 30% up to over 60% of the wholesale peak price[34] [102,103].

Demand side management: Demand side management options for large[35] consumer loads, like *load control switches* at industrial or institutional facilities, can contribute significantly to optimising the quality of energy supply and reducing load-shedding through allowing to cut of peak-demand. Load-shedding usually affects the poorest electricity consumers the most, as they have limited possibilities to compensate outages.[36] Radio-controlled interruptible institutional water heaters or water pumping systems constitute just two examples for such load control. The associated reduction of service quality if electricity is not available instantly requires some form of compensation by utilities, most likely in the form of special tariffs.

Mature technologies and market approaches constitute advantages of targeting a limited number of large industrial consumer loads, as opposed to a large number of residential consumers [29]. Yet, those can have an important role in contributing to realising the benefits of Smart Grids, e.g., through *smart appliances*. For example, smart refrigerators that hold enough thermal storage to withstand interruptions or avoid power use during peak loads could be deployed. Again, the reduction of service quality, even if minor, requires some form of compensation by utilities. Supportive policies will need to ensure that consumers profit from the additional costs they might have to bear. Minimum efficiency standards could help reduce the electricity use by such appliances. But first, a solid business case will have to be demonstrated before smart appliances become an attractive option for sub-Saharan Africa.

Smart Grids would further allow for a *prioritisation of loads* according to public importance, guaranteeing a higher security of supply for buildings such as hospitals rather than for enterprises or households. Its system-wide implementation requires utility

[30] This represents a shift from the application of traditional local-based control in existing power systems. However, grid control and design techniques that incorporate such coordinated control are yet to be established.

[31] In addition to synchrophasors, wide-area monitoring and control could build on intelligent electronic devices such as protective relays, programmable controllers and stand-alone digital fault recorders. Examples of applications include coordinated Volt-Ampere Reactive (VAR) control solutions [95] and adaptive system islanding and resynchronisation [93].

[32] For example, only around 33% of all electricity in India is billed, which is mainly attributed to theft and inefficient billing practices [98]. In addition to pure electricity theft, cable theft may constitute a significant problem. In various municipalities in South Africa, all-day street lighting is used as an early warning system, despite generation constraints [9].

[33] Energy conservation supply curves for measures regarding generation, metering and energy efficiency measures are provided in [100] for a mini-grid in Nicaragua.

[34] In the U.S., 22% of the peak demand equalling 170 GW is available in the form of consumer backup generators. This includes generators of up to 60 MW, but 98% of them are smaller than 100 kW [102].

[35] Large compared with the total capacity of the grid.

[36] Those who can afford it might, e.g., use back-up generators when load-shedding occurs, and this is just in case the districts where they are living in are affected at all.

control down to individual consumers facilitated by remotely controlled switches. A system-wide roll-out of such switches might not be justifiable. Selective load control could be an option which is easier to implement. A higher priority could be given to some selected loads while all remaining loads could have the same, but lower, priority. A simple implementation might be to install separate distribution lines for those few high-priority loads. Additional control devices would therefore only be required at selected sub-stations. This might help maximise the benefits while minimising costs.

Local charging stations: While rural electrification is a priority in many countries, it cannot be entirely equated with electricity access for the poor, as millions of people live near the grid but cannot afford a connection [104,105]. For these people, *local charging stations* ensure a minimum level of access to electricity services, for example, for charging lanterns or batteries. Especially when used for lighting, they may replace more expensive and environmentally harmful energy sources like paraffin.[37] Elaborating a successful business model[38] at these stations could further spawn local businesses and jobs, both directly related to the charging services as well as possibly through public on-site access to electric tools and equipment, e.g., grain mills or ICT facilities. Local charging stations usually generate their demand on-site. While experiences exist internationally (e.g., [106]), such stations were often implemented as stand-alone systems, without using their potential to help balance the system. If smartly integrated into local mini-grids, the storage capacity additions through batteries may further help contribute to increased power quality and reliability, by compensating power flow and voltage fluctuations. The modular nature of local charging stations would allow targeted investments to test the integration in mini-grids before larger roll-outs. Another possibility would be the introduction of electric bicycles for taxi services. These could be charged at stations during off-peak hours, combining income generation with demand side management.[39]

Billing schemes: As many Smart Grid components build on ICT, they might profit from 'piggybacking' on future telecom service expansions, such as the provision of electricity consumption information via *mobile phone services* [109]. Charging prepaid consumption credits[40] via mobile phones using scratch cards or comparable devices may help address the specific needs of the poor. The required installation of at least a very basic form of smart meter will enable remote meter readings, which may reduce administrative costs related to meter readings and billing,[41] and might help reduce theft.[42] Further, remote meter readings will help increase energy efficiency by reducing the vehicle usage associated with manual readings [96]. The current experience with mobile phone services in sub-Saharan Africa, e.g., for agricultural market information or financial transactions, suggests a solid business case for mobile phone companies, which have shown to possess the capacity to implement and manage such services.[43]

Meter-based tariffs incentivise an efficient use of electricity, which could result in considerable load reduction.[44] A basic *time-of-use pricing* scheme at household level may easily be introduced in sub-Saharan Africa to help balance demand. For energy-intensive industries, *real-time pricing* may be considered. This will help remove hidden subsidies that sometimes burden smaller customers, who are charged more than their fair share [29]. Consumers will tend to shift the more expensive peak demand to off-peak hours, resulting in a higher system load factor and operation closer to the system optimum.

In addition, *on-bill financing*[45] of energy-efficient and potentially smart appliances[46] may be an important tool to help consumers overcome high upfront costs and ultimately reduce their energy bill. Implementing this measure will require some policy support to incentivise the efficiency improvements and associated generation and income reductions for utilities.

Enabled by the introduction of smart meters, a Just Grid could further address the needs of the poor by ensuring reliable *low-cost access during off-peak hours*. Curtailed access would be provided during times of higher demand.[47] Loads requiring higher reliability throughout the day would need to pay a higher tariff for this privilege.[48] First illustrative energy system model runs for a rural supply scheme indicate that the potential for low-cost tariffs is significant, as a large share of off-peak demand might be delivered at half the price of the average generation cost [115]. Providing low-cost access might increase the interest of utilities to connect the poor, as this might become less costly or even profitable. Utilities would also profit from the increases in system flexibility and a more efficient system operation due to a higher off-peak demand, and consequently a higher system load factor. Further, this could also encourage people to adopt energy-efficient practices for peak times, either because of higher tariffs or dependency on batteries.[49] Through increasing electricity access, such tariffs might replace environmentally more harmfully produced energy services, e.g., firewood for water-heating.

Conceivably, the introduction of smart meters in combination with smart appliances would even allow delineating *tariffs by*

[37] Even more so when generation is based on renewable energy. According to UNIDO [106], 10 of their renewable energy based "Community Power Centres" would replace 1.5 million liters of diesel generation annually, offsetting some 5000 t of greenhouse gas emissions each year.

[38] This model would need to cover the logistics of battery ownership, management and charging.

[39] Due to strong policy support, China has 120 million electric bicycles on its roads [107], with 21 million bicycles being bought in 2008 alone, at prices typically below USD 300 [108]. By controlling their charging time they could become one element of a Smart Grid.

[40] Botswana and other countries were already using pre-paid meters in the 1980s [110]. Refer to Niez [9] for information on the introduction of prepaid electricity meters under South Africa's Integrated National Electrification Programme.

[41] For customers with a telecom contract, the electricity bill may as well be charged to the monthly telephone bill.

[42] This was reported as one of the reasons for Italy's initiative to fit smart meters in 85% of Italian homes [111]. The Italian utility Enel S.p.A. reports annual cost savings of EUR 500 million from their investments in the smart meter technologies, which were characterised by a very low payback period, allowing it to recoup the infrastructure investment in just four years [29].

[43] Since its introduction in 2007, the Kenyan M-Pesa mobile phone banking service was used by 40% of all Kenyans to transfer over US$3.7 billion all together [112]. It is worth noting that the average customer is not rural and poor, as some might assume.

[44] In a mini-grid in Nicaragua, the abandonment of a flat-rate tariff after the installation of meters helped reduce the overall electricity load by 28% by encouraging a more conscious use of electricity, thus enabling the mini-grid to operate for longer [100].

[45] On-bill financing enables utility customers to pay for specific investments through their electricity bill. For example, the utility could distribute energy efficient compact fluorescent lamps and refinance them via a small surcharge on its monthly bills. This would enable the utility to recover its initial costs over the expected lifetime of the lamps. Refer to [113] for further information on on-bill financing.

[46] In a mini-grid in Nicaragua, the introduction of compact fluorescent lights helped to cut demand by 17%, which meant the mini-grid could operate for longer [100].

[47] Such demand would come from loads that require higher reliability, such as industrial and commercial usage.

[48] In the Indian context, it has been proposed to ensure a higher quality of electricity supply for customers who regularly pay their bills, and lower quality for those who do not [114].

[49] This has been observed with water supply schemes, where communities adjust their behaviour to access a critical but economical resource. People carry out water-intensive functions such as cleaning clothes during hours of supply, and reserve activities that need less water, such as cooking, for times without supply.

service. Targeted subsidies for basic energy services, potentially combined with minimum energy efficiency requirements, could ensure that consumers can afford meeting some of their most pressing demands with cleaner energy sources. Higher subsidies could be applied up to a certain consumption threshold and could be linked to tariffs with lower requirements for the reliability of supply. As the consumer is being charged for the service rather than the electricity, on-bill financing could easily be used to add the life-cycle costs of the appliance to the electricity price in order to derive the actual service cost. This may enable a more economically rational basis for choosing appliances. While the technical requirements for the implementation of tariffs by service might be prohibitive in the near-term, this option might increase in attractiveness as the overall power system advances.

Information systems architecture: Once a smart power system with two-way flow of information and intelligent control is set up, *data management tools* could help utilities distil relevant information in a manageable and understandable format. *Diagnostic software* may further help monitor the health of grid assets, predict problems in power distribution, and initiate corrective action. The required architecture must ensure interoperability and enable a smooth transition from existing to future power systems [93]. Special attention to security issues will be required in countries with limited robust governance regimes. User-friendly interfaces, such as cell-phone billing and transparent metering, will be equally important to engage customers successfully.

6. Selected assessment criteria

The potential of the options shown in *italic and underlined* above were further qualitatively assessed against various criteria. These include their impact, their requirements, and the applicability of models as a basis for quantitative future assessments.[50] Their largely positive impacts were assessed across the entire power system, sub-divided into the categories: ''Consumers'', ''Quality of Supply'', ''Generation'' and ''Environment''. The requirements of an option, which to some extent reflects the costs to society, were sub-divided into: ''Technical Complexity'', the scope of required ''Investments'' and ''Human Capacities'', and the need for enabling support through ''Policy, Regulation & Standards''. These categories are briefly introduced with reference to broadly anticipated smart grid benefits and challenges. A first-pass assessment of the selected options of Smart and Just Grids is then provided in the following section.

Consumers: A user-centric approach, often requiring active participation of educated end-users, is key to the uptake of many Smart Grid options [26]. Consumers are largely expected to profit from the suggested initiatives. It is anticipated that Smart Grids may potentially play an important role in extending access to electricity and addressing the specific needs of the poor.[51] Initially, lower reliability requirements than in industrialised countries may be acceptable if they result in accelerated electrification rates. Further, Smart Grids may help create new jobs.[52] However, some increases in system flexibility may also mean reductions in service quality, e.g., when electricity for an appliance is not instantly available due to remote ''smart'' scheduling.

Operation & quality of supply: Smart Grids may significantly contribute to reducing costs of grid congestion, power outages and power quality disturbances[53] through increasingly efficient automated operations [117]. Building on advances in equipment monitoring and diagnostics as well as supportive standards[54] allows for more sophisticated asset management and operation, especially when combined with active management of consumer demand. For example, system flexibility could be improved through increasing the reliability and quality of supply for consumers with high requirements,[55] while providing less reliable and lower quality power at reduced costs for consumers with lower requirements [83]. This may enable the release of latent network capacity [29,118] and reduce the need for spinning reserve [79]. Additionally, technologies such as power flow control could have a significant impact on the effective utilisation of network capacity under normal and contingency conditions, especially once grids advance towards increased interconnection.

Generation: This category comprised the direct implications of utility-focused Smart Grids initiatives on overall generation and capacity requirements. Africa's average transmission and distribution losses of 11% are close to the global average of approximately 9%[56] [83,119]. However, including non-technical losses, many countries in sub-Saharan Africa are characterised by much higher system losses of up to 41% [120]. Higher technical losses are due to less efficient and poorly managed and maintained equipment [121]; higher non-technical losses can often be attributed to uncollected debt, tampered meters and inconsistencies in billing due to corrupt meter readers or illegal connections [9,39,99,114].

Smart Grid technologies could help minimise technical losses in transmission, for example by facilitating more effective reactive power compensation[57] and improved voltage control [96]. They could address distribution losses[58] through adaptive voltage control at substations and line drop compensation to levelise feeder voltages based on load [122]. Non-technical losses such as power theft could be partially addressed with the help of smart metering infrastructure [111].[59] Active demand-side management by utilities could further help minimise the need for expensive electricity supply to satisfy peak demand [117]. The IEA [29,124] estimates that Smart Grids potentially enable a 13% to 24% reduction of projected peak demand increases between 2010 and 2050.[60]

[50] These options cover varying degrees of complexity and detail, from technical options like load control switches to rather conceptual suggestions like low-cost access tariffs.

[51] The required policy and regulatory support is addressed in the corresponding category below.

[52] McNamara [116] estimates that Smart Grid incentives worth USD 16 billion in the U.S. could trigger associated projects amounting to USD 64 billion. This would result in the direct creation of approximately 280,000 positions and the indirect creation of a substantially larger number of jobs.

[53] In the U.S., these costs are estimated to be in the range of USD 25–80 billion annually [35].

[54] For example, through weather-related operational security standards, which release latent network capacity under specific weather conditions [118].

[55] This would require utilities to prioritize the reliability of services dependent upon target group, such as emergency services, financial institutions, industries, consumers, and industry [36].

[56] Ranges vary from, for example, 5% in Japan [119] and 6% in the U.S. [11] to 26% in India [83]. Distribution losses usually account for the largest share of total power delivery losses [80]. Substation transformers have been cited as the source of up to 40% of total grid losses [93].

[57] For example, DC-to-AC current-controlled inverters can both supply and absorb reactive power only and do not participate in resonances, as capacitors do [36].

[58] Increasing the efficiency of European distribution transformers by 0.33% would have reduced losses by more than 100 TWh in 2000 and would result in savings of 200 TWh in 2030 [121]. For a sense of scale, the electricity generation of Australia in 2009 was 232 TWh [11].

[59] Additionally, monitoring of transformer loading and third party assessments of potential misuse will help tackle such power theft, which is often difficult to determine in developing countries as it can involve collusion with linesmen and meter readers. For example, in Rio de Janeiro the local utility Ampla was able to reduce its revenue losses from 53% to 1.6% of the electricity supplied. This was mainly due to remote monitoring and disconnections [123].

[60] Doran et al. [36] mentions a study which estimates that a 1% reduction in peak demand would translate to cost reductions of 4%, equalling billions of dollars at system level.

Environment: A transition towards Smart Grids on its own may not be the primary strategy for achieving ambitious energy and carbon saving targets. However, it may provide a significant contribution to related electricity sector targets [125]. On a global scale, it is estimated that direct and indirect benefits of Smart Grids offer the potential for yearly emission reductions of 0.9–2.2 Gt CO_2 per year by 2050 [83].[61] Expected direct benefits include reduced losses, accelerated deployment of energy efficiency programmes and direct feedback on energy usage. Indirect benefits include facilitation of electric vehicles[62] and greater integration of renewable energy. This is because Smart Grids provide risk mitigation mechanisms which potentially allow relaxing current reliability requirements without comprising the overall system reliability. Current grid requirements often constitute a strong disincentive to less predictable, but cleaner, electricity sources [96].

Technical complexity: While Smart Grids are likely to be composed of complex and integrated systems, they often build on proven advanced technologies. Additionally, several promising technologies on the horizon may also form part of future grids, e.g., high temperature superconducting materials, advanced electric storage systems such as flow batteries or flywheels, and power electronics devices for AC–DC conversion [56,79].[63] In addition to the complexities associated with the technologies themselves, the requirements regarding their integration into, and management within, the system need to be considered.

Financing: The scale of investment required to enhance today's grids to meet the demands of future power systems is considerable. However, the detailed monetary implications are not yet fully understood [83]. Based on the IEA's New Policies Scenario, total investment in transmission and distribution is expected to reach USD 278 billion for Africa over the period 2011–2035 [4].[64,65] 2.1% of these investments will be required for the integration of renewable energy sources. In addition to the investments in the New Policies Scenario, USD 390 billion (in year-2010 dollars) would be needed over the period 2010–2030 to achieve universal access to electricity by 2030. Almost all of this additional amount would be required in sub-Saharan Africa[66] and only one third of it is expected to target on-grid solutions.

While the additional costs for massively upgrading existing grids to Smart Grids might not be justifiable, the business case when investing in new infrastructure is considerably better. This offers significant opportunities for sub-Saharan Africa. Yet, the capital and operating costs associated with communication networks of Smart Grids are high, especially as suppliers lack economies of scale and price-in delivery risk [123]. The benefits are more difficult to monetize than the costs and issue of on-going debate. In general, utilities are characterised as risk-adverse and may be conservative in assessing their benefits. Free-riding strategies might result in strategically delayed investments [130]. The situation gets further complicated as cost might occur in one, but benefits throughout many sectors of the power system.[67] This is not only an issue for utilities. It will as well need to be ensured that customers profit from the costs they have to bear. Supportive financing schemes might be required to enable them to cover upfront investments. While the overall benefits of Smart Grid investments outweigh the costs according to the IEA [56], developing a business case becomes a challenge.

Human capacities: Smart Grids redefine the roles of power sector stakeholders, from those at policy and institutional levels to power equipment manufacturers, ICT providers, generators and consumers. Developing the required human and institutional capacities to best respond to stakeholder needs and responsibilities[68] will be essential for their successful implementation. According to the IEA [83], technical capacity has to be developed from a relatively low level in developing countries, lending further prioritisation to capacity-building initiatives. For some larger and individual interventions, e.g., at the transmission level, it might be most efficient to 'import' expertise at the design stage. This will however not be sustainable for on-going efforts like the daily grid operation or continuing grid extensions at the distribution level. Ensuring technical expertise at the utility level will therefore be key.

Policy, regulation & standards: Policy support will be essential to trigger the required investments in developing countries. They need to facilitate a balanced approach towards the sharing of costs, benefits and risks between key stakeholders [29]. They are as well required to protect consumers against the negative impacts associated with the collection of consumer data and remote disconnection [131]. For developing countries, they are essentially important to ensure the justness of electrification plans.

Novel regulatory regimes will be needed, not least to incentivise innovative ways of enhancing access to the grid. Present regulation often rewards utilities for delivering network infrastructure assets rather than improving performance through more sophisticated management and advanced network technologies.[69] Thus, regulation could hinder Smart Grid developments that do not focus on investments in network assets.

Most current network design and operation practices are centred on the historic deterministic "N-1" approach [132] from the late 50ies.[70] This approach imposes a major barrier for grid innovation,[71] yet it is commonly taken as granted in research work [133] [72]. The future grids required in sub-Saharan Africa may offer fertile ground for a radical departure from such traditional regulation,

[61] According to EPRI [122], Smart Grids in the U.S. could potentially reduce 60–211 Mt CO_2 per year by 2030. This is equivalent to converting 14–50 million cars each year into zero-emission vehicles under a "business as usual" scenario.

[62] Shifting demand, for example through electric vehicles, may in fact increase CO_2 emissions in systems where base load is met with more CO_2 intensive generation than peak load [36].

[63] The National Energy Technology Laboratory has identified and grouped many Smart Grid technology components [126,127]: (1) Integrated communications, including Broadband over Power Line (BPL) and digital wireless; (2) Sensing and measurement, including system sensors for condition information on grid assets and system status and Advanced Metering Infrastructure (AMI); (3) Advanced components, based on fundamental research and development, including Unified Power Flow Controllers (UPFC) and Direct Current micro-grids; (4) Advanced control methods, to ensure high quality supply, including advanced Supervisory Control and Data Acquisition (SCADA) systems and distributed intelligent control systems; and (5) Improved interfaces and decision support to reduce significant amounts of data to actionable information, including online transmission optimisation software and support tools to increase situational awareness. An alternative grouping of Smart Grid technology areas can be found in [83].

[64] Barriers to smart grid investments are listed in MEF [37].

[65] According to the Brattle Group [129], the U.S. electric utility industry is expected to invest USD 1.5–2.0 trillion in infrastructure within the next 20 years. For comparison, the total asset value of the electricity sector in the U.S. is estimated to exceed USD 800 billion, with 30% in distribution and 10% in transmission facilities [79].

[66] In East Africa alone, billions of dollars will be required for supply and transmission infrastructure over the next two decades [19].

[67] For example, in many cases the benefits of line losses are considered as customer benefits [123].

[68] A description of these needs and responsibilities can be found in ETP Smart Grids [30].

[69] In sub-Saharan Africa, laws governing the power sector and at times over-sophisticated standards sometimes originate back from colonial times [71].

[70] A system which adheres to the $N-1$ rule maintains reliable operation even if a major element fails, e.g., a transmission line. This rule exists in several variations depending on reliability requirements.

[71] An overview of how standards can support or hamper Smart Grids developments is provided in EPRI [24].

[72] For example, Divan [134] demonstrates significantly higher network capacity while meeting $N-1$ contingency constraints using economical distributed power flow control devices. Even higher utilisation could be realised if the $N-1$ constraint is dropped.

grid design and operation practices. A relaxation of power quality and reliability standards based on the advances of Smart Grids may therefore enable sub-Saharan Africa to balance asset- and performance-based options[73] and profit from the associated significant cost savings potential[74]. Standards are further required for equipment, data transport, interoperability and cyber security[75] . They could help promote supplier competition, accelerate innovation, expand the range of technological choices, facilitate interconnections and ultimately lower costs for consumers [29]. Their enforcement, notably regarding stringent logical (computer) security requirements, presents obstacles to all countries. It will however be even more challenging for countries without strong governance systems in place.

Modelling: Given the increase in complexity of energy planning through Smart and Just Grids, power system modelling increases in importance to inform multi-criteria decision making[76]. The required expansion and adaptation of traditional approaches to energy planning and modelling needs to include a more active role for demand, linkages with storage, and the integration of mini-grids into plans for grid expansion[77]. In addition to optimising electricity systems from a technical perspective, Just Grids need to be optimised from a development perspective. Ensuring services for marginalised and rural communities will often not be the most cost-effective solution. New constraints (or different objective functions) need to be added to expand traditional least-cost optimisation models (for applications refer to, e.g., [115,145–147]).

Modelling the flexibility of demand is often only possible to a limited degree in current electrification models. It may require in-depth knowledge and modification of the source code, which in many cases limits such applications to a confined circle of experts. OSeMOSYS [148,149], a newly developed open-source model, may provide analysts with a new route to inform energy planning in developing countries. In addition to energy system planning tools, stability and reliability analysis are required to address the increasingly complex dynamic management of voltage and frequency control, especially in view of the growing integration of renewable electricity [150].

7. Indicative assessment

Based on the criteria of the previous section, Table 1 provides an indicative assessment. In a single framework, it compares selected Smart and Just Grids options which are currently focused on in industrialised countries as well as options explicitly targeting developing countries. A brief outline of these options can be found in Section 5, where they are highlighted in *italic and underlined*.

The assessment criteria are grouped according to the main categories, i.e., impact, requirements, and the applicability of models as a basis for quantitative future assessments. The qualitative ranking is provided by using "++", "+", "o", "-", and "–", with "++" refering to strong potential drivers for the deployment of specific options, "–" to very persuasive arguments against specific options, and "o" to categories which are neither drivers nor barriers[78]. As such, "++" in the category "Generation" may refer to significant reductions in peak demand and losses (as opposed to an increase in generation), "++" in "Consumers" to a very positive impact on consumers and especially the poor, potentially with opportunities for job creation, or "–" in "Technical Complexity" to significant requirements regarding the complexity of the technologies with little existing experience in their implementation. The annex provides a brief explanation of the rankings for each assessment criterion.

It is important to note that this qualitative assessment does not intend to, and cannot have, the character of a rough cost-benefit analysis. The individual circumstances essentially influence the impact of and requirements for the integration of specific elements of Smart and Just Grids.

Table 2 describes the main characteristics of each selected Smart and Just Grids option in an individual box. Each box provides a concise statement for each assessment criteria, grouped according to the main categories, i.e., impact (Consumers/Operation & Quality of Supply/Generation/Environment), requirements (Technical Complexity/Investments/Human Capacities/Policy, Regulation & Standards), and the applicability of models as a basis for quantitative future assessments.

The categorisation in this section is guided by literature and largely based on its interpretation by the authors. The intention is to provide suggested direction for future initiatives, which would clearly vary to some extent when reassessed under specific on-the-ground conditions. A detailed and holistic assessment of the power sector will be a prerequisite in order to identify deployment pathways, which might ultimately turn out to contain a subset of the suggested options.

8. Suggested next steps

Regardless of which specific aspects of the Smart and Just Grid concept for sub-Saharan Africa are pursued, international cooperation will be essential[79] to realising its potential. South–South Cooperation and learning could form an integral element of the required international action as many sub-Saharan African countries face challenges similar to those of developing and emerging economies such as India[80] .

More specifically, Smart and Just Grids for sub-Saharan Africa can profit from coordinated efforts in the following selected areas:

Analysis of potential and roadmaps: Identify sub-Saharan Africa's potential to profit from Smart and Just Grids, including an assessment of associated costs and benefits. Based on electrification models, develop road maps for conditions which are common to many African countries, e.g., rural electrification, and support related efforts, for example by the IEA [29] or the scenarios developed for Africa by IRENA [153]. This includes the identification of technology solutions that could be rapidly and cost-effectively deployed in the short-term and would act as precursors towards long term deployment pathways.

Country assessments: Provide international support for a preliminary assessment of the power sectors and as well the specific needs of individual consumer groups like households or industry. Based on this assessment, develop country-specific

[73] However, the long term goal to guarantee a strong and reliable HV grid in Africa as a backbone to the power systems should be kept in mind.

[74] Such an approach could be supported by a range of advanced technologies such as dynamic line rating, coordinated corrective power flow and voltage control techniques, and application of advanced decision making tools.

[75] Balijepalli et al. [39] underline the need for open, performance-based standards to ensure modularity and interoperability. Basso and DeBlasio [135] present the status of IEEE standards on interoperability and interconnection.

[76] Several supportive modelling tools are used for integrated resource planning [136]. WASP, amongst others, constitutes a model that is frequently applied in Africa [137,138]. Tools such as MESSAGE [139] and MARKAL [140] are derived from the Häfele-Manne approach [141] and often used for "multi-regional" models.

[77] An example of this – though limited – is presented in Howells et al. [142]. Howells uses a tool based on MESSAGE, which, together with WASP and several other tools [139,143,144], serves to examine the expansion of access to energy services.

[78] Barriers for developing Smart Grids in South Africa can be found in Bipath [151]. Challenges, drivers and priorities in developing countries are mentioned in Bhargava [152].

[79] According to Bipath [151] international cooperation for Smart Grids is expected to focus on standardisation, cybersecurity and interoperability.

[80] Balijepalli et al. [39] report the detailed requirements and needs for Smart Grids in India.

Table 1
Quantitative categorisation of selected Smart and Just Grid options.

	Impact				Requirements				
	Consumers	Operation & Quality of Supply	Generation	Environment	Technical Complexity	Investments	Human Capacities	Policy, Regulation & Standards	Applicability of Models for pre-assessments
Local charging stations	++	+	o	+	+	+	+	+	o
On-bill financing	+	o	+	+	++	++	o	-	-
Mobile phone services	++	+	o	o	o	-	+	+	-
Load control switches	-	+	+	o	+	+	o	o	o
Integration of existing distributed generators	o	++	+	o	-	+	--	o	o
Prioritisation of loads	o	+	o	o	o	o	o	-	+
Improved power lines and transformers	o	+	++	++	-	--	-	-	o
DC micro grids	o	o	+	+	-	+	--	-	o
Time-of-use/Real time pricing	+	+	+	o	-	-	--	-	o
Low cost access during off-peak hours	++	+	o	+	-	-	--	-	+
Data management tools and diagnostic software	o	++	o	o	-	-	-	-	--
Smart appliances	o	++	+	+	--	--	-	--	o
Wide-area monitoring and control	o	++	o	o	-	--	-	-	--
Tariffs by service	++	o	o	o	--	--	--	--	-
Distribution automation	o	++	o	o	--	--	--	-	--

business and development cases for Smart and Just Grids. Prioritise investments in specific smart elements with clearly defined mechanisms for return on investment[81].

Power system design: Develop and deploy internationally supported open-source or widely available modelling tools and capacities for power system design and operation, adjusted to the specific context. It is critically important that the system architecture developed enables future system upgrades without adding significant costs during early implementation stages.

Pilot projects: Implement joint pilot projects based on identified fast-track solutions. These pilot projects will help understand stakeholder behaviour within their redefined roles and allow testing the markets before engaging in massive rollouts. Remote rural electrification schemes with higher penetration rates of renewable energy sources might serve as a particularly good starting point.

Enabling environments: Help promote supportive policy, regulatory, institutional, legal and commercial frameworks. Sub-Saharan Africa could especially profit from ongoing efforts in industrialised countries to adjust related network standards. Additionally, legislation precedents could be employed to help reduce electricity theft[82]. Further, international design competitions could help highlighting challenges and develop innovative solutions.

Capacity-building initiatives: Train key stakeholders based on skills assessments. Developing the asset management capacities of African utilities and energy entrepreneurs to maintain

[81] While we emphasise the importance of business case development, it needs to be recognised that many historical infrastructure projects were based on home-grown 'nation-building' initiatives.

[82] China's major reform of the rural power management system in 1988, combined with rural grid enhancements, helped reduce losses in low-voltage grids by 30–45% and consequently lowered electricity prices. Refer to Niez [9] for further information. For another example, refer to India's 2003 Electricity Act, which heavily penalizes electricity theft [9].

technical systems and equipment will be vital for ensuring the sustainable deployment of Smart and Just Grids.

Financing: Identify a range of financing sources, from donor grants to private sector loans, and map their potential role in supporting different Smart Grids options. These financing sources should target interventions covering both, power system upgrades and expansions, including mini- and micro-grid solutions. Appropriate support instruments should be

Table 2
Characteristics of selected Smart and Just Grid options.

Local charging stations	On-bill financing	Mobile phone services
++ Expands access to those who can't afford connection; might help create jobs; can replace more expensive energy sources + Adds storage capacity to (mini-) grid o Demand increases may be covered with on-site generation + May replace environmentally more harmfully produced energy services	+ Reduction of upfront costs for energy- & cost-efficient (smart) appliances o No direct impact on quality of supply + Reduction of (peak) demand through efficient (smart) appliances + Reduction of associated environmental impact	++ Addresses especially the needs of those with lower or irregular incomes + Reduced costs for meter readings o No impact on generation o More energy efficient billing with slightly positive environmental impact
+ Existing experience, but not yet used to help balance the system + Targeted modular investments allow testing the concept + In-country expertise to be extended to enable better (mini-) grid integration + No specific policy interventions required	++ Little technology requirements, besides of appliances themselves ++ Investments by utilities are directly passed on to consumers through bills o Some capacity building required to develop attractive financing schemes - Policy support beneficial, as such schemes might not be in the immediate interest of utilities	o Existing experience with similar services, e.g., financial transactions; potentially good business case for phone companies - Requires smart meters - individually small, but wide-spread investments + Phone companies have capacities to manage such services + No specific policy interventions required
o Expanded models required for pre-assessments	- Social studies required for reflecting effects within demand-side models	- Social studies required for reflecting effects within demand-side models
Load control switches	**Integration of existing distributed generators**	**Prioritisation of loads**
- Reduces quality of service if electricity is not available instantly; compensation by utility required + Helps improve system-wide quality of supply and system stability + Reduction of peak demand possible o Environmental impact dependent on how peak demand is generated	o No direct impact on consumers, apart from profit for owners of generators ++ Improves quality of supply and system load factor + Helps utility to reduce its own peak generation o Environmental impact of diesel generation may be outweighed by reduced need for spinning reserve	o Effect on consumer dependent on consumer type and prioritisation + Improved security of access for high priority loads, e.g., hospitals, police o No impact on generation o No impact on environment
+ Well known technologies can be integrated selectively for large loads + Targeted selected investments o Could be monitored centrally if only installed at large loads o Requires some regulation to specify degree of consumer flexibility and associated compensation by utility	- Requires installing control automation for existing generators + Defers utility capacity investments -- In-country expertise required for system design and operation o Requires some regulation to specify profit for owner from grid integration	o Selective load control possible; might require separate distribution lines o Type of investment strongly dependent on depth of system integration; targeted investments possible o Could be monitored centrally if only installed for selected loads - Policy decisions required to regulate prioritisation
o Expanded models required for pre-assessments	o Expanded models required for pre-assessments	+ Existing model adaptions and runs
Improved power lines and transformers	**DC micro grids**	**Time-of-use/Real time pricing**
o No direct impact on consumers + May improve system performance and efficiency ++ May significantly contribute to technical loss reduction ++ Improved transmission efficiency through loss reduction has positive environmental impact	o Grid set-up has no direct influence on consumers o Only minor impact on grid operation + Loss reduction through saving layers of DC/AC & AC/DC power conversion + Improved transmission efficiency through loss reduction has positive environmental impact	+ Fairer, more cost-reflective prices eliminate hidden subsidies + Higher load factor allows operation closer to the system optimum + Reduces peak demand due to higher prices during peak hours o Environmental impact dependent on how peak demand is generated
- Builds to a large degree on complex technologies -- Requires larger infrastructure investments - Foreign expertise could facilitate implementation - Development of technical standards required	- More complex fault management and control increases complexity + Targeted investments allow testing the concept -- Expertise also required at local level to maintain the grid - Development of technical standards required	- Requires (smart) meter installations - Individually small, but wide-spread investments -- Human capacity requirements for setting up tariff schemes, installations and monitoring of effectiveness - Requires some regulation to ensure just tariff scheme
o Can indirectly be included in system models as costs and loss reductions	o Can indirectly be included in system models as costs and loss reductions	o Expanded models required for pre-assessments

Table 2 (*continued*)

Low cost access during off-peak hours	Data management tools and diagnostic software	Smart appliances
++ Affordable, but less reliable tariffs, allow expanding access for the poor + Higher load factor due to higher off-peak demand allows operation closer to the system optimum o Increase in overall demand, but as well average generation efficiency + May replace environmentally more harmfully produced energy services --- - Requires smart meter installations - Individually small, but wide-spread investments -- Human capacity requirements for setting up tariff schemes, installations and monitoring of effectiveness - Policy support beneficial to ensure just implementation --- + Existing model adaptions and runs	o Has no direct impact on consumers ++ Help predict problems and initiate corrective action o Only minor impact on generation, e.g., through better fault management o Only minor impact on environment --- - Complexity strongly dependent on types of tools; requires system-wide monitoring and control as a precondition - Difficult to test out the profitability of investments beforehand - In-country expertise required, especially for system operation - Interoperability standards required --- -- Impacts are difficult to model	o Reduces quality of service if electricity is not available instantly; reduces costs through efficiency increases ++ Increases system-wide quality of supply through demand management + Helps reduces peak demand + Minimum efficiency requirements can help reduce environmental impact --- -- Complexity highly dependent on type of appliance; requires smart meters -- Individually small, but wide-spread investments; financing schemes beneficial to support customers - In-country expertise required, especially for system operation -- Strong policy support required to ensure benefits for consumers --- o Expanded models required
Wide-area monitoring and control	**Tariffs by service**	**Distribution automation**
o Has no direct impact on consumers ++ Supports more efficient system operation and increased stability o Only minor impact on generation, e.g., through better fault management o Only minor impact on environment --- - Requires integration throughout the transmission system; dependent on some form of data management tools and software -- Overall larger investments required; difficult to test out the profitability of investments beforehand - In-country expertise required, especially for system operation - Technical standards required, e.g., for interoperability --- -- Impacts are difficult to model	++ Allows for targeted subsidies of essential services o No direct impact on quality of supply o No direct impact on generation o No direct environmental impact, but could easily be linked to energy efficient smart appliances --- -- Requires smart meter installations in connection with smart appliances -- Individually small, but wide-spread investments; financing schemes beneficial to support customers -- In-country expertise required for setting up tariff scheme, installations and monitoring of effectiveness -- Strong policy dependence --- - Social studies required to assess ability/willingness to pay for services	o Has no direct impact on consumers ++ Can help minimise outages and increase speed of restoration o Only minor impact on generation, e.g., through better fault management o Only minor impact on environment --- -- Requires integration throughout the distribution system; more challenging than for transmission system -- Overall larger investments required; difficult to test out the profitability of investments beforehand -- Significant in-country expertise required for both implementation and maintenance - Technical standards required, e.g., for interoperability --- -- Impacts are difficult to model

developed which address the financing needs of different stakeholder groups. Reliable investment environments will be required which enable a fair way of sharing risks, costs and especially benefits.

For a successful transition towards smart and just energy systems, international cooperation will need to be complemented by close engagement with regional and national stakeholders. While Smart and Just Grids require strong public commitment, including funding, the private sector as the main engine of economic growth has an essential role in supporting related initiatives in sub-Saharan Africa. A close integration of the private sector in related efforts will be key.

9. Conclusion

Sub-Saharan Africa is characterised by significant electricity-related challenges in terms of resources, infrastructure, cost and sustainability. Finding ways to enhance future power systems represents a key task for governments, regional power pools and utilities. Some Smart Grid approaches may enable sub-Saharan Africa to leapfrog traditional power systems practices in the short term. Others will require preconditions to be established today in order to avoid technology lock-in and ensure compatibility with future concepts and technologies. Further research will be essential in narrowing down the required preconditions for the successful implementation of elements of Smart and Just Grids. Piloting their application will then serve to test and enhance the concept to allow realising the potentially significant future benefits.

From an economic perspective, reliable energy supply through Smart and Just Grids will help foster economic growth. From an environmental perspective, Smart Grids will allow for a more efficient utilisation of resources with lower associated greenhouse gas emissions. Finally and most importantly, from a societal perspective, accelerated access to electricity taking advantage of Smart Grids will speed up development efforts, as electrification is linked to many aspects of the development agenda.

The massive electricity infrastructure requirements in sub-Saharan Africa offer a unique opportunity to learn from developed countries and move forward without necessarily repeating all previous development stages of the power system. We should take advantage of this significant opportunity to ensure that sub-Saharan Africa's future grid is designed in a way that is both smart and just.

10. Annex-qualitative ranking

This annex provides explanatory remarks regarding the qualitative ranking. The meaning of each ranking category is briefly commented on for each assessment criteria.

10.1. Consumers

++ Overall benefit for consumers with strong pro-poor characteristics
+ Overall benefit for consumers
o Only minor or no impact on consumers
- Some reduction in quality of service
-- Consumers are burdened by this measure

10.2. Operation and quality of supply

++ Significantly positive impact
+ Positive impact
o Only minor or no impact
- Negative impact
-- Significantly negative impact

10.3. Generation

++ Significant reduction of peak demand and/or reduction in losses
+ Reduction of peak demand and/or reduction in losses
o Only minor or no impact on generation
- Increases in peak demand and/or losses
-- Significant increase in peak demand and/or losses

10.4. Environment[83]

++ Significant positive impact through efficiency increases or fuel substitution
+ Positive impact through efficiency increases or fuel substitution
o Only minor or no impact
- Negative impact
-- Significant negative impact

10.5. Technical complexity

++ Little technology requirements, or technologies which have already been successfully introduced in sub-Saharan Africa
+ Well known technologies, or existing experience in sub-Saharan Africa with comparable technologies; do not necessarily require system-wide integration
o Existing experience, but system-wide integration required
- Complex technologies; do not necessarily require system-wide integration, e.g., only at transmission grid or distribution level like smart meter installations
-- More complex technologies, usually requiring system-wide adjustments, e.g., smart meter installations together with smart appliances

[83] The actual degree of this impact will depend on the generation mix.

10.6. Investments

++ Very small investments, or investments which can easily be refinanced
+ Well confined, targeted smaller investments allow testing out the business case
o Type of investment strongly dependent on applied design and system integration
- Investments whose profitability cannot easily be tested out beforehand, e.g., because they are system-wide like smart meter installations
-- Overall larger investments, usually for infrastructure, or large investment requirements from a consumer perspective, e.g., for smart appliances

10.7. Human capacities

++ Already common practice in sub-Saharan Africa
+ Capacities are to a large extent available within country
o Capacities can easily be built, e.g., because they are only required centrally at utility level
- Significant in-country capacity requirements for implementation or operation
-- Significant in-country capacity requirements for both implementation and operation

10.8. Policy, regulation and standards

++ Already existing and well established supportive policies and regulation
+ Already in preparation or no or only little requirements
o supporting frameworks required, but extensive existing and easily translatable precedence
- Some policy support, regulation or technical standards required
-- Strong dependence on policy support for effectively implementation

10.9. Applicability of models for pre-assessments

++ Existing case studies and precedence in literature
+ Existing electrification model adaptations and runs
o Current electrification models need to be expanded
- Further studies, e.g., on consumer acceptance, required as input to expanded electrification models
-- Impacts are difficult to model

Disclaimer

The views expressed herein are those of the author(s) and do not necessarily reflect the views of their respective institutions. The designations employed and the presentation of the material in this document do not imply the expression of any opinion whatsoever concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries, or its economic system or degree of development. Designations such as "developed", "industrialised" and "developing" are intended for statistical convenience and do not necessarily express a judgment about the stage reached by a particular country or area in the development process. Mention of firm names or commercial products does not constitute an endorsement by the respective institutions.

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